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CT Angiography of the Aorta: Contrast Timing by Using a Fixed versus a Patient-specific Trigger Delay

Hinzpeter, Ricarda ; Eberhard, Matthias ; Gutjahr, Ralf ; Reeve, Kelly ; Pfammatter, Thomas ; Lachat, Mario ; Schmidt, Bernhard ; Flohr, Thomas G ; Kolb, Beate ; Alkadhi, Hatem

Abstract: Background Optimal timing of the CT scan relative to the contrast media bolus remains a challenging task given the shorter scan durations of modern CT scanners, as well as interpatient variability. Purpose To compare contrast opacification in CT angiography of the aorta between a cohort with fixed trigger delay and a cohort with patient-specific individualized trigger delay for contrast media timing with bolus tracking. Materials and Methods In this prospective study (January-August 2018), CT angiography of the thoracoabdominal aorta with bolus tracking was performed in two different study cohorts: one with a fixed trigger delay of 4 seconds (fixed cohort) and one with a patient-specific trigger delay (individualized cohort). All CT and contrast media protocol parameters were kept identical among cohorts. Objective image quality was evaluated by one reader; two readers assessed subjective image quality. Student test was used to test for differences in mean attenuation; the Wilcoxon-Mann-Whitney test was used to test for differences in noise, contrast-to-noise ratio, and subjective image quality. Results The fixed cohort had 108 study participants (16 women; mean age ± standard deviation, 72 years ± 10); the individualized cohort had 108 participants (16 women; mean age, 72 years ± 12). The trigger delay in the individualized cohort ranged from 6.4-11.3 seconds (mean, 9.2 seconds). There was higher overall attenuation in the individualized cohort than in the fixed cohort (486 HU ± 92 for individualized vs 438 HU ± 99 for fixed; $< .001$), with increasing differences from the aortic arch (8 HU) to the iliac arteries (95 HU). The regression model indicated uniform attenuation in the individualized cohort and decreasing attenuation in the fixed cohort (decrease of 87 HU by the iliac arteries; $< .001$). There was no difference between cohorts for image noise (20 vs 19; $= .41$), but contrast-to-noise ratio (21 vs 19; $= .04$) and subjective image quality were higher in the individualized cohort than in the fixed cohort (excellent or good image quality, 100% vs 67%; $< .001$). Conclusion Compared with a fixed delay time after bolus tracking, a patient-specific individualized trigger delay improves image quality and provides uniform contrast attenuation for CT angiography of the aorta. ©RSNA, 2019.

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CT Angiography of the Aorta: Contrast Timing by Using a Fixed versus a Patient-specific Trigger Delay

Ricarda Hinzpeter, MD • Matthias Eberhard, MD • Ralf Gutjahr, PhD • Kelly Reeve, MSc • Thomas Pfammatter, MD • Mario Lachat, MD • Bernhard Schmidt, PhD • Thomas G. Flohr, PhD • Beate Kolb, MAS • Hatem Alkadhi, MD, MPH, EBCR, FESER

From the Institute of Diagnostic and Interventional Radiology, University Hospital Zurich, University of Zurich, Raemistr 100, CH-8091 Zurich, Switzerland (R.H., M.E., T.P., B.K., H.A.); Siemens Healthcare, Forchheim, Germany (R.G., B.S., T.G.F.); Epidemiology, Biostatistics and Prevention Institute, University of Zurich, Zurich, Switzerland (K.R.); and Department of Cardiovascular Surgery, University Hospital of Zurich, Zurich, Switzerland (M.L.). Received September 28, 2018; revision requested November 21; revision received January 18, 2019; accepted January 22. **Address correspondence to** H.A. (e-mail: *hatem.alkadhi@usz.ch*).

Conflicts of interest are listed at the end of this article.

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Background: Optimal timing of the CT scan relative to the contrast media bolus remains a challenging task given the shorter scan durations of modern CT scanners, as well as interpatient variability.

Purpose: To compare contrast opacification in CT angiography of the aorta between a cohort with fixed trigger delay and a cohort with patient-specific individualized trigger delay for contrast media timing with bolus tracking.

Materials and Methods: In this prospective study (January–August 2018), CT angiography of the thoracoabdominal aorta with bolus tracking was performed in two different study cohorts: one with a fixed trigger delay of 4 seconds (fixed cohort) and one with a patient-specific trigger delay (individualized cohort). All CT and contrast media protocol parameters were kept identical among cohorts. Objective image quality was evaluated by one reader; two readers assessed subjective image quality. Student *t* test was used to test for differences in mean attenuation; the Wilcoxon-Mann-Whitney test was used to test for differences in noise, contrast-to-noise ratio, and subjective image quality.

Results: The fixed cohort had 108 study participants (16 women; mean age ± standard deviation, 72 years ± 10); the individualized cohort had 108 participants (16 women; mean age, 72 years ± 12). The trigger delay in the individualized cohort ranged from 6.4–11.3 seconds (mean, 9.2 seconds). There was higher overall attenuation in the individualized cohort than in the fixed cohort (486 HU ± 92 for individualized vs 438 HU ± 99 for fixed; $P < .001$), with increasing differences from the aortic arch (8 HU) to the iliac arteries (95 HU). The regression model indicated uniform attenuation in the individualized cohort and decreasing attenuation in the fixed cohort (decrease of 87 HU by the iliac arteries; $P < .001$). There was no difference between cohorts for image noise (20 vs 19; $P = .41$), but contrast-to-noise ratio (21 vs 19; $P = .04$) and subjective image quality were higher in the individualized cohort than in the fixed cohort (excellent or good image quality, 100% vs 67%; $P < .001$).

Conclusion: Compared with a fixed delay time after bolus tracking, a patient-specific individualized trigger delay improves image quality and provides uniform contrast attenuation for CT angiography of the aorta.

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Scan timing is an important and decisive variable for achieving good and homogeneous contrast enhancement in CT angiography. Determination of optimal scan timing yielding adequate contrast opacification remains a challenging task given the shorter scan durations of modern CT scanners (1), the more widespread use of low-kilovoltage scanning requiring smaller volumes of contrast media due to the k-edge of iodine, and the influence of patient-specific parameters (2–4). Thus, there is a growing risk of missing the peak arterial enhancement in CT angiography.

Bolus tracking represents the most widespread method for timing the scan start of CT angiography with the injection of contrast media. The technique monitors the contrast enhancement in a user-defined vessel and after a threshold is reached, the scan is initiated after a predefined and fixed trigger delay. Compared with the test bolus technique, the main benefits of bolus tracking with a fixed trigger delay are the need for less contrast media, less radiation dose exposure, and time efficiency (5). Although the bolus tracking technique has been used for decades, it still has shortcomings. One of its major shortcomings is that the fixed trigger delay of conventional bolus tracking after the threshold was reached does not take into account variable patient-specific cardiovascular parameters such as the cardiac output or blood circulation time. For example, in patients with a high cardiac output, a fixed and predefined trigger delay may result in missing the peak arterial enhancement, as scan initiation might be too late. By contrast, in patients with a low cardiac output, the scan might be initiated too early and image acquisition terminated before the peak arterial enhancement can be reached.

Some authors proposed specified trigger delays that have to be set before the start of contrast media injection, which are defined according to different indications (6–8). However, information about the cardiovascular status of a patient is usually only available during actual bolus tracking data acquisition. Furthermore, implementation of such an approach into clinical routine may be difficult because of the required operator interaction and workflow issues.

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Abbreviations

CI = confidence interval, $CTDI_{vol}$ = volume CT dose index

Summary

An individualized trigger delay improves contrast opacification in CT angiography of the aorta, yielding a higher and more constant attenuation as well as an improved subjective image quality.

Key Points

- In study participants undergoing CT angiography of the aorta, the calculated trigger delay time after bolus tracking for peak arterial enhancement varies between 6.4 and 11.3 seconds.
- Patient-specific individualized trigger delay in CT angiography of the aorta led to higher attenuation (486 HU vs 438 HU), more stable enhancement, and improved subjective image quality (excellent or good image quality, 100% vs 67%) compared with scan timing with a fixed and predefined trigger delay.

Thus, it would be helpful to have an automated algorithm available for bolus tracking in aortic CT imaging, which corrects for patient-specific characteristics resulting in an optimized and individualized scan timing. We hypothesize that CT angiography using an individualized trigger delay may result in a more homogeneous attenuation of the aorta and the iliac arteries compared with that of a fixed trigger delay.

Accordingly, the purpose of this study was to compare contrast opacification in CT angiography of the aorta between a cohort with fixed trigger delay and a cohort with patient-specific individualized trigger delay for contrast media timing with bolus tracking.

Materials and Methods

This study had institutional review board and local ethics committee approval. All study participants provided written informed consent prior to study participation. Three authors (R.G., B.S., and T.G.F.) were involved in the development of the trigger delay algorithm provided for the study and are employees of Siemens Healthcare (Forchheim, Germany). These authors did not have control over the data at any point during the study.

Study Participants

Two hundred and thirty consecutive study participants who underwent clinically indicated CT angiography of the thoracoabdominal aorta and iliac arteries were included in the study. Participants were excluded for the following reasons: chronic kidney disease (estimated glomerular filtration rate <30 mL/min/1.73 m^2; n = 5), occlusion of the infrarenal aorta (Leriche syndrome; n = 1), technical defect (n = 1), and denial of study participation (n = 7) (Fig 1). A total of 216 participants were included in our study.

The first 108 consecutive study participants (16 women, 92 men; mean age ± standard deviation, 72 years ± 10) were assigned to fixed cohort (January–April 2018). CT angiography in this cohort was performed with a fixed trigger delay. The next 108 study participants (16 women, 92 men; mean age, 72 years ± 12) were included in the individualized cohort (April–August 2018). CT angiography in this cohort was performed with a patient-specific individualized trigger delay (see details next). Indications for patients in both cohorts are listed in Table 1.

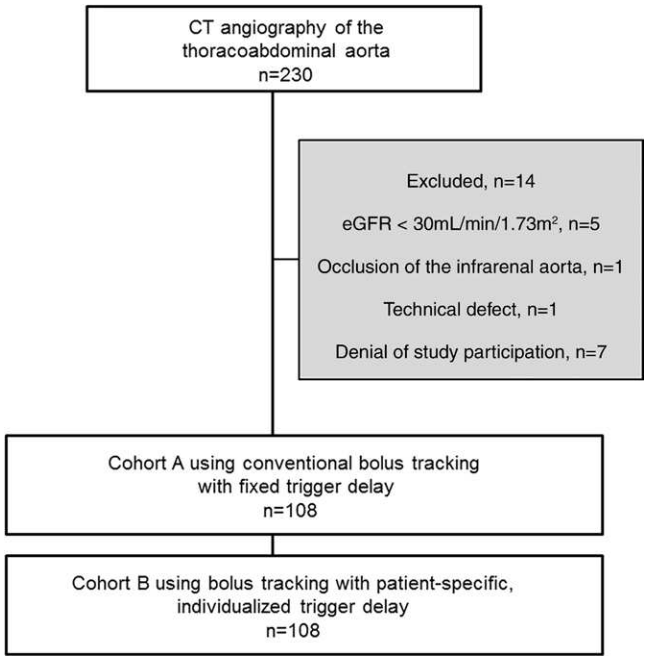


Figure 1: Flowchart of study. eGFR = estimated glomerular filtration rate.

Bolus Tracking Technique

Aortic contrast opacification was monitored by using bolus tracking in the descending aorta on the level of the left atrium with an attenuation threshold of 120 HU at 120 kVp for all examinations. In the fixed cohort, the start time of data acquisition was determined with a default fixed delay of 4 seconds after the threshold was reached (Fig 2a). In the individualized cohort, a noncommercially available prototype bolus-triggering software (Custom Pack, Somaris 7.VA50 SP2, version 2; Siemens Healthcare) was used, starting the data acquisition based on a prediction of the local contrast (C) over time (t) (in Hounsfield units), which is calculated by convoluting the applied contrast agent injection protocol (IP) (in grams of iodine per second) and the patient's arterial impulse response function (in Hounsfield units per grams of iodine) as previously described (9,10). After exceeding the attenuation threshold CT number and the acquisition of at least four bolus tracking enhancement values, the given contrast information is used to derive the patient-specific arterial impulse response by online fitting to a population-averaged set of parameterized arterial blood circulation curves (9). While pivoting the predicted time to peak (t_{ttp}) (3), the individualized time delay (t_{id}) takes into account the monitoring position, the evaluated scan range, and the pitch of the scanner (Fig 2b):

$$C(t) = IP(t) \otimes AIR(t)$$

$$t_{ttp} = t\left(max\left(C(t)\right)\right).$$

Table 1: Study Participant Demographics and Radiation Dose Estimates in Both Cohorts

Variables	Fixed Cohort	Individualized Cohort	*P* Value
No. of participants	108	108	
Age (y)*	72 ± 10	72 ± 12	.9
Sex			>.99
Male	92 (85)	92 (85)	
Female	16 (15)	16 (15)	
Weight (kg)*	81.8 ± 16.2	78.5 ± 16.4	.14
Height (cm)*	174 ± 8	172 ± 8	.09
Body mass index (kg/cm^2)*	27 ± 4	26.5 ± 5	.42
Comorbidities			
Diabetes	14 (13)	8 (7)	.18
Hypertension	63 (58)	56 (52)	.34
Dyslipidemia	29 (27)	36 (33)	.3
Indications for CT angiography			.43
Follow-up of aortic dissection	8 (7)	10 (9)	
Follow-up of untreated aneurysm	18 (17)	14 (13)	
Follow-up after endovascular repair of abdominal aorta and iliac arteries	62 (57)	67 (62)	
Follow-up after endovascular repair of thoracic aorta	20 (19)	17 (16)	
Radiation dose estimates			
Volume CT dose index (mGy)*	5.4 ± 2.0	5.1 ± 1.7	.23
Dose-length product (mGy·cm)*	382 ± 144	358 ± 133	.2
Size-specific dose estimate (mGy)*	6.2 ± 1.6	6.0 ± 1.4	.36

Note.—Data in parentheses are percentages.
* Data are means ± standard deviation.

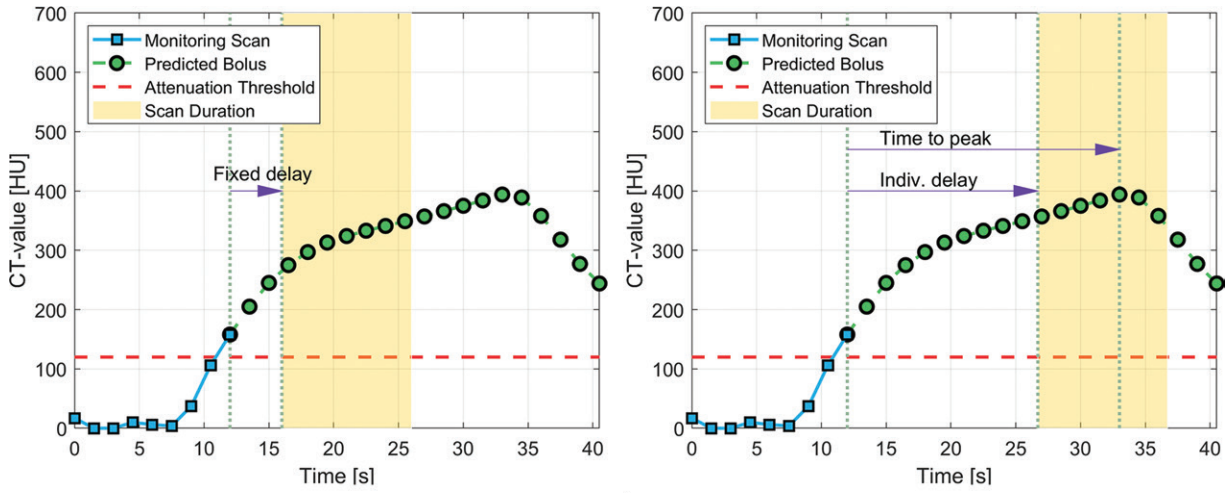


Figure 2: Graphs show bolus tracking for CT angiography with **(a)** fixed and **(b)** individualized patient-specific trigger delay time. Patient-specific individualized trigger delay is based on prediction of local contrast enhancement over time while considering scan parameters such as relative monitoring position, scan range, and pitch of scanner, as well as patient-specific arterial impulse response.

CT Scanning Protocol

All CT examinations were performed by using a 192-section dual-source CT scanner (Somatom Force; Siemens Healthcare) operating in the single-source mode and with identical data acquisition parameters in both cohorts (detector collimation, 2 × 96 mm; section acquisition, 2 × 192 mm using the *z*-flying focal spot; pitch, 1.2; table feed, 69 mm/sec; gantry rotation time, 250 msec; tube voltage, 100 kVp; and quality reference tube current-time product, 90 mAs per rotation by using automated exposure control [CareDose4D; Siemens Healthcare]). The scan was performed in a craniocaudal direction and included the lung apex to the lesser trochanter in all study participants. The average scan duration was 6.5 seconds.

The contrast media administration protocol was also kept identical in both cohorts. After injecting 10 mL of 0.9% saline solution with a flow rate of 4 mL/sec in an antecubital vein to

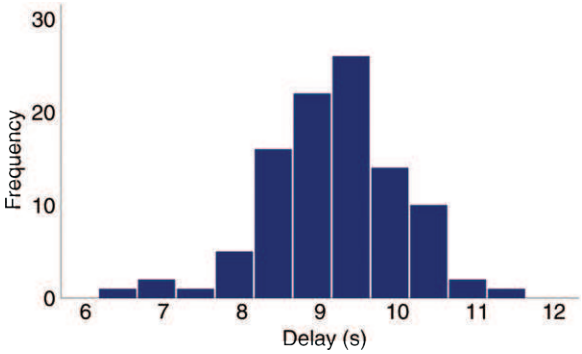


Figure 3: Cumulative histogram shows trigger delay in individualized cohort (range, 6.4–11.3 sec; mean, 9.2 sec). Standard trigger delay time in fixed cohort was 4 seconds.

test unobstructed flow, 70 mL of prewarmed, nonionic, iodinated contrast medium (iopromidum, Ultravist 370; Bayer Pharmaceuticals, Berlin, Germany; 370 mg/mL) with a flow rate of 4 mL/sec was administered, followed by 15 mL saline at the same flow rate.

All images were reconstructed with 2-mm section thickness and 1.6 mm increment by using a medium-smooth soft tissue kernel (Bv36) and with advanced modeled iterative reconstruction at a strength level of 3.

Objective Image Quality

Objective image quality was evaluated by one author (R.H., a radiology resident with 3 years of experience in cardiovascular imaging) who was blinded to assignment to study cohorts, clinical indication, and imaging test results.

Vessel attenuation was assessed at five locations: ascending aorta at the level of the pulmonary trunk, aortic arch at the origin of the left subclavian artery, descending aorta at the level of the left atrium, abdominal aorta at the origin of the superior mesenteric artery, and proximal left common iliac artery. Regions of interest were drawn as large as possible: ascending aorta (mean area, 745 mm^2 ± 202), aortic arch (mean area, 492 mm^2 ± 172), descending aorta (mean area, 361 mm^2 ± 126), abdominal aorta (mean area, 266 mm^2 ± 130), and left common iliac artery (mean area, 100 mm^2 ± 91). Arteriosclerotic vessel wall changes and endovascular prosthesis material were excluded from the regions of interest. Then, attenuation of the right psoas muscle was measured at the level of the lower pole of the right kidney. The standard deviation of the attenuation measured in the regions of interest in the psoas muscle was defined as the image noise. The contrast-to-noise ratio was calculated as the mean vessel attenuation subtracting the attenuation of the psoas muscle and then dividing the difference by image noise (11).

Subjective Image Quality

Subjective image quality was performed by two independent readers (M.E., a radiologist with 5 years of experience in cardiovascular imaging before and after board certification, and R.H.) evaluating homogeneity of vascular opacification of the aorta and iliac arteries. Readers were blinded to assignment to study cohorts, clinical indication, and imaging test results, and were allowed to adjust the window level and width during evaluation of vessel opacification. The time interval between readout sessions was 7 days. Image quality was assessed by using a five-point Likert scale (2): 1, excellent (homogeneous contrast media distribution with no difference between the proximal aorta and iliac arteries); 2, good; 3, moderate; 4, poor; 5, nondiagnostic with insufficient proximal or distal contrast enhancement. Prior to rating images for the study, the two readers used data from five randomly selected patients outside the study to reach a consensus on how to apply the Likert scale. The raters than used the scale on all study participants to assess the subjective image quality.

Radiation Dose Estimates

The volume CT dose index (hereafter, $CTDI_{vol}$) and dose-length product were collected from the automatically generated radiation dose report. Effective diameter (or ED) was calculated by using the anteroposterior diameter (or AD) and the lateral diameter (or LD) of the upper abdomen at the level of the origin of the superior mesenteric artery ($ED = \sqrt{[AD \times LD]}$). Size-specific dose estimates (or SSDE) (in milligrays) were calculated with a size-dependent conversion factor (f) (12) generated by using measurements with a cylindrical reference phantom (13) by using the following equation: $SSDE \approx f \times CTDI_{vol}$.

Statistical Analysis

Quantitative normally distributed variables were summarized by using means and standard deviations, and variables having nonnormal distributions were summarized by using medians and interquartile ranges. Categorical variables were summarized by using frequencies and percentages. With 90% power and a significance level of 5%, a total number of 216 study participants (108 per cohort) are necessary to detect a difference of 40 HU in mean attenuation between cohorts, assuming a standard deviation of 90 HU in both cohorts. The χ^2 test was used to test for differences between cohorts regarding sex and indications for CT angiography. The Student t test was used to test for differences between cohorts with respect to numeric study participant characteristics and radiation dose estimates.

Interreader agreement of subjective image quality between readers was assessed with weighted Cohen κ by using quadratic weights and were interpreted according to Altman (14). A combined rating for each study participant was calculated as the average from the readers. A difference in combined ratings across cohorts was tested by using the Wilcoxon-Mann-Whitney test. Objective image quality was assessed in several ways. First, Student t test was used to test for differences in attenuation values across cohorts at each location, and the Wilcoxon-Mann-Whitney test was used to test for differences between cohorts regarding image noise and contrast-to-noise ratio. Then, linear regression using generalized least squares was performed to explore differences in mean attenuation values along the aortic and iliac arteries between cohorts.

Data were analyzed by using commercially available (IBM SPSS Statistics for Windows, version 25.0; Armonk, NY) and open-source (R Foundation for Statistical Computing, version 3.5.1; Vienna, Austria) software. A two-tailed $P < .05$ was considered to indicate statistical significance.

Table 2: Objective Image Quality

Measurement Location	Fixed Cohort	Individualized Cohort	Difference*	95% CI	*P* Values
All locations (HU)	438 ± 99	486 ± 92	…	…	<.001
Ascending aorta (HU)	468 ± 99	476 ± 95	7.9	−18.6, 34.4	.55
Aortic arch (HU)	459 ± 92	496 ± 95	37.0	11.5, 62.5	.004
Descending aorta (HU)	442 ± 89	489 ± 91	46.7	22.2, 71.2	<.001
Superior mesentery artery (HU)	439 ± 95	492 ± 90	52.9	27.7, 78.0	<.001
Left common iliac artery (HU)	381 ± 97	476 ± 85	94.8	70.0, 119.7	<.001
Right psoas muscle (HU)	49 ± 7	52 ± 7	…	…	<.001
Image noise†	19 (18, 23)	20 (18, 23)	…	…	.41
Contrast-to-noise ratio†	19 (16, 23)	21 (17, 26)	…	…	.04

Note.—Unless otherwise specified, data are means ± standard deviation.

* Indicates differences in mean attenuation values (individualized cohort − fixed cohort) and confidence intervals (CIs) of differences at each location.

† Data are medians, with interquartile ranges in parentheses.

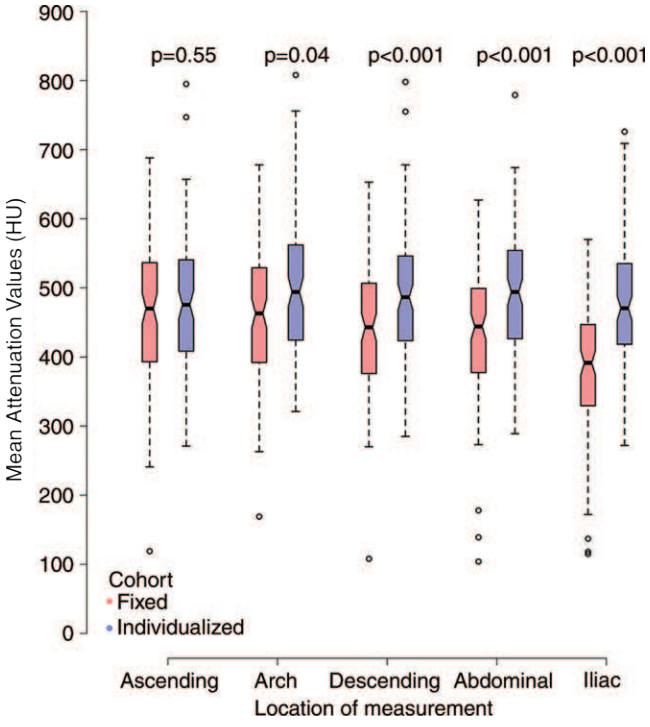


Figure 4: Box plot shows attenuation values (in Hounsfield units) in both cohorts. Lower attenuation outliers in individualized cohort are absent.

Results

Study Participants

Demographics of the study population are shown in Table 1. The two cohorts did not differ regarding study participant age ($P = .9$), sex ($P > .99$), weight ($P = .14$), height ($P = .09$), and body mass index ($P = .42$). Likewise, there were no differences between the cohorts regarding indications for CT angiography ($P = .43$). The effective tube current-time product was 57–309 effective mAs per rotation in the fixed cohort and 58–277 effective mAs in the individualized cohort. Radiation doses were similar among cohorts ($CTDI_{vol}$, $P = .23$; dose-length product, $P = .2$; SSDE, $P = .36$) (Table 1).

Delay after Bolus Tracking

The trigger delay for bolus tracking after reaching the threshold in the fixed cohort was predetermined at 4 sec. The patient-specific trigger delay in the individualized cohort was taken from a log file, which was automatically generated by the algorithm. This individualized trigger delay ranged between 6.4 and 11.3 seconds (mean, 9.2 seconds) (Fig 3), which indicates considerable interindividual variations of the calculated predicted time to peak arterial enhancement from real-time modulation.

Objective Image Quality

Overall, the mean attenuation was higher in the individualized cohort compared with the fixed cohort (486 HU vs 438 HU; $P < .001$). Although no difference in attenuation was observed across cohorts in the ascending aorta (difference of 8 HU; 95% confidence interval [CI]: −19, 34 HU; $P = .55$), attenuation values were higher in the individualized cohort at all other locations (Table 2, Fig 4). The largest difference between cohorts was observed in the common iliac artery (95 HU; 95% CI: 70, 120 HU) (Table 2). A linear regression model showed lower attenuation with each successive location from the ascending aorta: 9 HU (95% CI: −14, −5 HU) lower in the aortic arch, 26 HU (95% CI: −32, −19 HU) lower in the descending aorta, 29 HU (95% CI: −38, −20 HU) lower in the abdominal aorta, and 87 HU (95% CI: −103, −71 HU) lower in the common iliac artery, compared with the ascending aorta (Table 3). Attenuation in the ascending aorta in the individualized cohort was 8 HU higher than in the fixed cohort.

Model selection indicated that allowing for different treatment effects across locations better explained the data (ie, inclusion of an interaction term between cohort and location, likelihood ratio test, $P < .001$). Interaction estimates (29 HU in the aortic arch, 39 HU in descending aorta, 45 HU in abdominal aorta, 87 HU in common iliac artery, all compared with the ascending aorta) counteracted the trend of lower attenuation across locations in the individualized cohort, but not in the fixed cohort. This resulted in stable attenuation in the individualized cohort but lower attenuation in the fixed cohort along the aortic and iliac arteries (see Table 3).

No difference in image noise between fixed cohort (median, 19) and individualized cohort (median, 20; $P = .41$) was found. Contrast-to-noise ratio was higher in the individualized cohort (median, 21) compared with the fixed cohort (median, 19; $P = .04$) (see Table 2).

Table 3: Objective Image Quality: Results from Linear Regression by Using Generalized Least Squares for Attenuation

Measurement Location	Estimate	Standard Error	95% CI	*P* Value*
Intercept	468.1	9.4	449.8, 486.5	<.001
Individualized cohort	7.9	13.2	−18.1, 33.8	.55
Aortic arch	−9.4	2.4	−14.1, −4.78	<.001
Descending aorta	−25.8	3.4	−32.4, −19.3	…
Superior mesentery artery	−28.6	4.5	−37.5, −19.7	…
Left common iliac artery	−87.0	8.2	−103.0, −71.0	…
Individualized cohort				
Aortic arch	29.1	3.4	22.5, 35.7	<.001
Descending aorta	38.8	4.7	29.5, 48.1	…
Abdominal aorta	45.0	6.4	32.4, 57.5	…
Left common iliac artery	86.9	11.6	64.3, 109.6	…

Note.— The baseline level for cohort is fixed delay and the baseline location is the ascending aorta. CI = confidence interval.

* *P* values are calculated per factor by using likelihood ratio tests.

Subjective Image Quality

In the fixed cohort, assessment of subjective image quality of both readers showed excellent or good quality in 50 of 108 (46%) and 23 of 108 participants (21%), moderate or poor quality in nine of 108 (8%) and five of 108 participants (5%), and nondiagnostic quality in two of 108 participants (2%). For seven of 108 participants (7%), subjective image quality was rated excellent by reader 1 and good by reader 2, while reader 2 rated image quality excellent for five of 108 participants (5%) that were considered good by reader 1. For two of 108 participants (2%), the reader 1 and reader 2 rating pairs were moderate to good and good to moderate for four of 108 participants (4%). The image of a single participant (one of 108, 1%) was considered poor by reader 1 and moderate by reader 2. In the individualized cohort, subjective image quality was rated good or excellent in all participants (100%), with agreement on 86 of 108 images (80%) rated excellent and 10 of 108 images (9%) rated good. Excellent-to-good rating pairs were observed for three of 108 images (3%) and good-to-excellent pairs for nine images (8%) (Figure E1 [online]).

Agreement between the readers never differed by more than one point on the Likert scale and Cohen weighted κ was 0.89 (95% CI: 0.81, 0.93). Scores from both readers were averaged due to very good agreement. There were differences in image quality ratings between cohorts, with images from individualized cohort rated as excellent considerably more often (86 of 108 vs 50 of 108; $P < .001$).

Representative examples of participants from both cohorts are provided in Figures 5 and 6.

Discussion

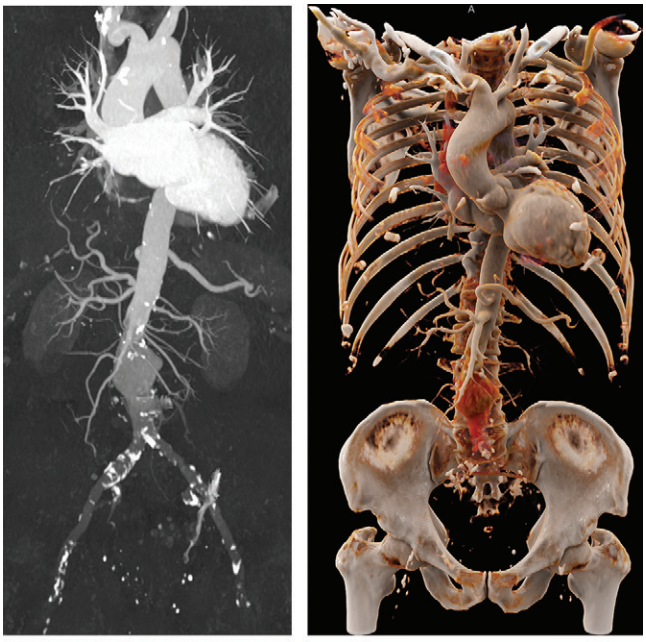
In the present study, an automatic bolus tracking algorithm was evaluated in a prospective patient cohort undergoing CT angiography of the thoracoabdominal aorta to optimize scan timing and consequently achieve good and homogeneous contrast opacification. We showed that using a patient-specific trigger delay results in significantly higher and more stable attenuation (486 HU ± 92 vs 438 HU ± 99) in the aorta and iliac arteries and in improved subjective image quality (excellent or good image quality, 100% vs 67%). Compared with the fixed cohort, there were no lower outliers regarding objective image quality assessment among patients undergoing CT angiography with individualized trigger delay, and none of these patients had a nondiagnostic image quality.

The degree and characteristics of arterial enhancement following contrast media injection with the same iodine flux shows considerable variation between individuals. This is corroborated by our results that showed a trigger delay in the individualized cohort, predicted by the algorithm, ranging from 6.4 to 11.3 seconds. Aside from body size and central blood volume, cardiac output represents the fundamental physiologic parameter that affects arterial enhancement. Cardiac output is inversely related to the degree of arterial enhancement, particularly in first-pass dynamics (15). Patients with high cardiac output have lower arterial enhancement compared with patients with a low cardiac output, despite a delayed time to peak enhancement in the latter (16). Thus, interindividual variations in first-pass arterial imaging need to be taken into account for an optimized opacification in arteries of interest.

Bolus tracking is the most common technique for contrast media timing in CT angiography. It considers individual enhancement characteristics with real-time monitoring of the contrast enhancement in a predefined region of interest. The bolus tracking method permits more efficient use of the contrast medium than does the test bolus method because the latter requires two separate contrast material injections and involves additional examination time (5). The major shortcoming of bolus tracking is the fixed trigger delay, which does not adapt for interindividual differences in time to peak arterial enhancement after the threshold was reached.

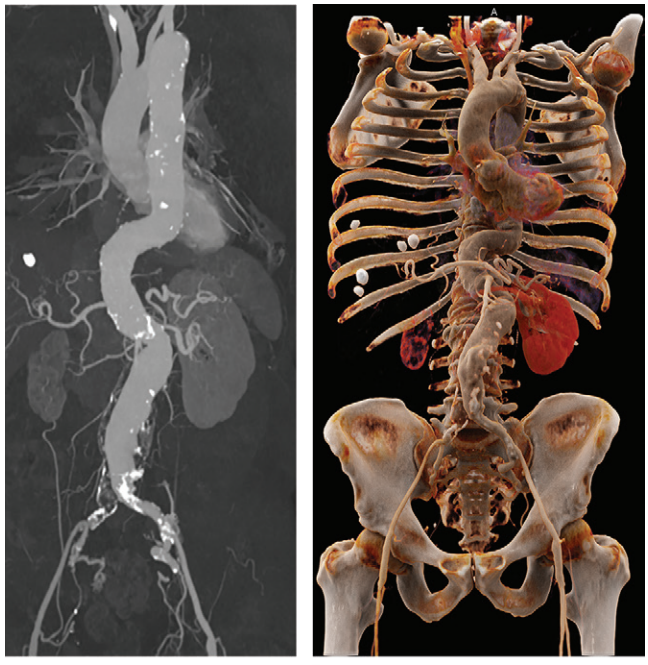
We tested a trigger delay algorithm for bolus tracking by using measured real-time vascular CT numbers of the monitoring phase to derive a patient-specific arterial impulse response by using online reconciliation with a large-scale database of arterial enhancement curves. Further considerations of the monitoring scan position, the scan range, and the acquisition speed of the diagnostic scan facilitate the determination of the individualized trigger delay to achieve maximal contrast and to yield homogeneous contrast distribution within the desired scan range.

Our study limitations must be acknowledged. First, cohort assignment was performed in a nonrandomized fashion, which



a. b.

Figure 5: Images in an 84-year-old male study participant with untreated infrarenal aortic aneurysm. **(a)** Contrast material–enhanced CT angiography with fixed trigger delay in coronal maximum intensity projection after bone removal and **(b)** cinematic rendering. Gradual reduction of attenuation from cranial to caudal resulted in adjudication of score 5 (nondiagnostic image quality) by both readers.



a. b.

Figure 6: Images in a 63-year-old male study participant with untreated infrarenal aortic aneurysm. **(a)** Contrast material–enhanced CT angiography with individualized trigger delay in coronal maximum intensity projection after bone removal and **(b)** cinematic rendering. Stable attenuation along aortic and iliac path was rated as score 1 (excellent image quality) by both readers.

introduces the possibility of biases such as changes in CT technology or differences in technologists' experience. Second, results of patient-specific individualized trigger delay were not compared with the test bolus technique. Third, we assessed image quality in the thoracoabdominal aorta and iliac arteries only, but other arterial territories may require different scan timing parameters. Fourth, all study participants had advanced cardiovascular disease, which may not require a patient-specific trigger delay algorithm for diagnostic purposes. On the other hand, such a cohort may be appropriate for showing the high interindividual variability of arterial enhancement across patients. Fifth, we used a CT scan protocol with fixed kilovoltage settings not adjusting for body weight. However, this was done on purpose for minimizing other possible confounders influencing vessel attenuation. Finally, diagnostic performance studies using the individualized trigger delay algorithm are required for testing clinical performance.

In conclusion, the patient-specific bolus tracking method optimizes vascular opacification in CT angiography of the aorta, improving subjective image quality. The overall high attenuation across different measurement locations with the individualized trigger delay algorithm bears potential for reducing the amount of administered contrast media, an effect that could be further exploited by lowering the tube voltage and diagnostic performance studies.

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References

1. Meyer M, Haubenreisser H, Schoepf UJ, et al. Closing in on the K edge: coronary CT angiography at 100, 80, and 70 kV-initial comparison of a second- versus a third-generation dual-source CT system. Radiology 2014;273(2):373–382.
2. Higashigaito K, Schmid T, Puippe G, et al. CT angiography of the aorta: prospective evaluation of individualized low-volume contrast media protocols. Radiology 2016;280(3):960–968.
3. Lell MM, Jost G, Korporaal JG, et al. Optimizing contrast media injection protocols in state-of-the art computed tomographic angiography. Invest Radiol 2015;50(3):161–167.
4. Siegel MJ, Hildebolt C, Bradley D. Effects of automated kilovoltage selection technology on contrast-enhanced pediatric CT and CT angiography. Radiology 2013;268(2):538–547.
5. Bae KT. Intravenous contrast medium administration and scan timing at CT: considerations and approaches. Radiology 2010;256(1):32–61.
6. Bischoff B, Bamberg F, Marcus R, et al. Optimal timing for first-pass stress CT myocardial perfusion imaging. Int J Cardiovasc Imaging 2013;29(2):435–442.
7. Lehmkuhl L, Andres C, Lücke C, et al. Dynamic CT angiography after abdominal aortic endovascular aneurysm repair: influence of enhancement patterns and optimal bolus timing on endoleak detection. Radiology 2013;268(3):890–899.
8. Schneider JG, Wang ZJ, Wang W, Yee J, Fu Y, Yeh BM. Patient-tailored scan delay for multiphase liver CT: improved scan quality and lesion conspicuity with a novel timing bolus method. AJR Am J Roentgenol 2014;202(2):318–323.

9. Korporaal JG, Bischoff B, Arnoldi E, Sommer WH, Flohr TG, Schmidt B. Evaluation of a new bolus tracking-based algorithm for predicting a patient-specific time of arterial peak enhancement in computed tomography angiography. Invest Radiol 2015;50(8):531–538.
10. Korporaal JG, Mahnken AH, Ferda J, et al. Quantitative evaluation of the performance of a new test bolus-based computed tomographic angiography contrast-enhancement-prediction algorithm. Invest Radiol 2015;50(1):1–8.
11. Nakaura T, Awai K, Maruyama N, et al. Abdominal dynamic CT in patients with renal dysfunction: contrast agent dose reduction with low tube voltage and high tube current-time product settings at 256-detector row CT. Radiology 2011;261(2):467–476.
12. American Association of Physicists in Medicine. Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations (task group 204). College Park, Md: American Association of Physicists in Medicine, 2011.
13. Christner JA, Braun NN, Jacobsen MC, Carter RE, Kofler JM, McCollough CH. Size-specific dose estimates for adult patients at CT of the torso. Radiology 2012;265(3):841–847.
14. Altman DG. Practical statistics for medical research. Boca Raton, Fla: Chapman & Hall, 1991.
15. Bae KT, Heiken JP, Brink JA. Aortic and hepatic contrast medium enhancement at CT. Part II. Effect of reduced cardiac output in a porcine model. Radiology 1998;207(3):657–662.
16. Fleischmann D, Kamaya A. Optimal vascular and parenchymal contrast enhancement: the current state of the art. Radiol Clin North Am 2009;47(1):13–26.